CHARACTERIZATION OF GAS-SOLID TWO-PHASE FLOW BY USING ELECTRICAL CAPACITANCE TOMOGRAPHY

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Dedicated to my beloved family especially my parents Hamzah Embong, Ainun Othman, Mosbah Kasnin, Siti Zaleha Abdullah, my dearest wife Siti ‘Atiqah Mosbah and beloved daughter ‘Ufaira Mikayla Ahmad Azahari. Also, my supportive supervisor Prof. Ts. Dr. Ruzairi Abdul Rahim

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ABSTRACT

Electrical capacitance tomography (ECT) is a non-invasive and non-intrusive internal visualisation modality that allows for better quantification by providing information on the cross-sectional distribution of any kind of multiphase flow. This research is conducted to overcome certain problems in a coal power plant, including the sedimentation of pulverised coal in the piping system before it enters the boiler system and the non-uniformity of its velocity, which leads to a decrease in the production of energy and higher emission of carbon dioxide. To achieve these aims, three objectives are set: (i) determination of the optimum conditions for an AC-ECT system to measure the capacitance of poly(methyl methacrylate) (PMMA) material; (ii) determination of the average solid velocity using a cross-correlation method; and (iii) image reconstruction based on eight ECT sensors using iterative and non-iterative algorithms. A simulation of an ECT sensor arrangement was carried out, and a real sensor was then built. Electrical capacitance spectro-tomography was used to obtain the best frequency range to allow PMMA to be analysed using the ECT system. The velocity profile and distribution were calculated using Parseval's theorem, and signal-to-signal and pixel-to-pixel cross-correlation methods were used, respectively. Iterative and non-iterative image reconstructions were tested for accuracy in a simulation of familiar flow conditions before they were applied to real experimental conditions. The velocity was measured using a dual-plane ECT sensor by applying Parseval's theorem and an adapted parabolic fit interpolation method, and this gave accurate results with a highest percentage error of 1.94%. An iterative method of image reconstruction based on the Landweber algorithm produced the most accurate results for the visualisation of gas-solid distributions in piping systems, and an acceptable time was required to complete the calculation. This research can help in the optimisation of energy production in coal thermal power plants, and especially in determining the location of coal sedimentation and the velocity of pulverised coal in the piping system.

ABSTRAK

Tomografi kapasitan elektrik (ECT) merupakan modaliti tomografi visual yang tidak invasif dan tidak intrusif dimana ianya menjanjikan pencirian yang baik dengan menyediakan maklumat penyebaran keratan rentas bagi pelbagai aliran berbilang fasa. Kajian ini dijalankan bagi menyelesaikan masalah di dalam janakuasa arang batu termasuk pemendapan arang batu di dalam sistem perpaipan yang dihubungkan kepada sistem dandang serta ketidakseragaman halajunya yang menyumbang kepada pengurangan penghasilan tenaga dan peningkatan pelepasan gas karbon dioksida. Bagi mencapai matlamat ini tiga objektif telah ditetapkan iaitu penentuan keadaan terbaik bagi AC-ECT sistem bagi mengukur nilai kapasitan bahan poli metil metakrilat (PMMA), penentuan purata halaju pepejal melalui kaedah korelasi silang dan pembinaan imej bagi 8 penderia ECT melalui algoritma tanpa lelaran dan lelaran. Simulasi komputer dilakukan terlebih dahulu bagi merekabentuk susunatur penderia ECT sebelum penderia sebenar dibina. Tomografi spektro-kapasitan elektrik yang mengaplikasikan berbilang frekuensi digunakan bagi mendapatkan julat frequensi terbaik untuk sistem ECT mengukur nilai kapasitan PMMA. Profil halaju dan serakan halaju seterusnya dikira menggunakan teorem Parseval melalui kaedah korelasi silang secara isyarat ke isyarat dan piksel ke piksel. Kaedah tanpa lelaran dan lelaran bagi pembinaan imej diuji dari segi ketepatan pada beberapa corak aliran yang biasa bagi aliran multi fasa sebelum kaedah tersebut digunapakai pada kajian eksperimen sebenar. Pengukuran halaju menggunakan satah berkembar penderia ECT melalui teorem Parseval dan adaptasi interpolasi parabola memberikan keputusan yang baik dengan peratusan ralat tertinggi adalah 1.94%. Pembinaan imej menggunakan algoritma Landweber memberikan hasil terbaik dalam memantau penyebaran gas-pepejal di dalam sistem perpaipan serta masa lelaran yang boleh diterima untuk melengkapkan kiraan. Kajian ini mampu membantu dalam mengoptimumkan penghasilan tenaga di dalam industri janakuasa arang batu terutamanya di dalam penentuan lokasi pengumpulan dan halaju arang batu di dalam sistem paip.

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LIST OF ABBREVIATIONS

AC	-	Alternative-Current
ASDF	-	Average square different function
CC	-	Correlation coefficient
CO_2	-	Carbon dioxide
DAS	-	Data acquisition system
DC	-	Direct correlator
DFT	-	Discrete Fourier Transform
ECT	-	Electrical capacitance tomography
EIT	-	Electrical Impedance Tomography
ERT	-	Electrical Resistance Tomography
FCC	-	Fluid catalytic cracking
FEM	-	Finite element method
FFT	-	Fast Fourier Transform
FPGA	-	Field Programmable Gate Array
fps	-	Frame per second
GVSPM	-	Generalised Vector Sampled Pattern Matching
HSC	-	High speed camera
Hz	-	Hertz
ID	-	Inner pipe diameter
IE	-	Image error
IFFT	-	Inverse Fast Fourier Transform
ILBP	-	Iterative linear back projection algorithm
kHz	-	Kilohertz
LBP	-	Linear back projection
LDA	-	Laser doppler anemometer

MATLAB	-	Matrix Laboratory
MHz	-	Megahertz
OD	-	Outer pipe diameter
PC	-	Personal computer
PFI	-	Parabolic fit interpolation
PIV	-	Particle image velocimetry
PMMA	-	Poly-methyl methacrylate
PT	-	Parseval theorem
PTP	-	Pixel to pixel
STS	-	Signal to signal
2D	-	Two dimensional
3D	-	Three dimensional

LIST OF SYMBOLS

A_p	-	Plate area
c	-	Capacitance
C	-	Normalised capacitance
C'	-	Normalised capacitance for GVSPM method
$C[f]$	-	Capacitance in frequency domain
D	-	Diameter
e	-	Percentage error
f	-	Frequency
G	-	Normalize permittivity
$\hat{G}$	-	True normalized permittivity distribution
$\bar{\bar{\hat{G}}}$	-	Mean value of true normalized permittivity distribution
$\bar{G}$	-	Mean value of permittivity distribution
I	-	Improvement of parabolic fit interpolation
i	-	Transmitter electrode
j	-	Receiver electrode
$\mathbf{J}$	-	Sensitivity matrix
k	-	Iteration number
L	-	Distance between two sensors
L_{as}	-	Axial screen length
L_{ele}	-	Electrode length
l	-	Electrode length
M	-	Independent capacitance measurement
N	-	Electrode number
N_p	-	Number of image element or pixel
O	-	Sequence length
P	-	Protocol number

Q	-	Charge
R	-	Cross-correlation function
r_1	-	Inner diameter of pipe
r_2	-	Outer diameter of pipe
S	-	Normalised sensitivity matrix
S'	-	Normalised sensitivity matrix for GVSPM method
S^T	-	Transpose of normalised sensitivity matrix
T	-	Sampling time
T_r	-	Room temperature
t	-	Time
V	-	Velocity
V_p	-	Volume
W	-	Electrode width
W_{rs}	-	Radial screen with width,
x	-	Separation between plates
Y	-	Lag number

Greek letter

Δx	-	Pipe thickness
$\Delta x_{annular}$	-	Thickness of annular flow
Γ_{ij}	-	Area of the total capacitance for electrode
v_{pp}	-	Signal amplitude
ϕ_{ij}	-	Potential
∇	-	Divergent operator
$\rho(\mathbf{r})$	-	Charge distribution
$\Vert\ \Vert_2^2$	-	Square of norm 2
Φ	-	Ratio between inner and outer diameter
α	-	Step size
ε_0	-	Permittivity of vacuum space
ε_r	-	Relative permittivity
τ	-	Time delay
$\mu(k)$	-	Weighting coefficient

$\Delta\phi_{ij}$ - Potential different

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CHAPTER 1

INTRODUCTION

1.1 Introduction to Research Study

Multiphase flow is mainly used to refer to fluid flows consisting of more than one phase or state (gas, liquid or solid) or component. Almost every processing technology deals with multiphase flow, including cavitating pumps and turbines, electrophotographic processes, papermaking, and the formation of pellets (Brennen, 2005). One type of multiphase flow which predominates in a large number of industrial processes is gas-solid flow, which has occupied the attention of scientists and engineers for many years. The complexities of this type of flow have still not been fully explored, and no universal equipment is capable of completely unravelling this phenomenon. The characterisation of gas-solid two-phase flow is therefore crucially important, and is necessary to allow processing plants to run with a more efficient and effective use of energy, thereby reducing operating expenses.

Numerical simulation and modelling is the most commonly used approach by researchers for the development of hardware and mathematical software that can simulate experimental conditions that are close to ideal with a low budget (Cai, Yuan & Zhao, 2016; Pu *et al.*, 2010; Shang, 2016). Experiments have been carried out in a pneumatic line using an electrostatic sensor for the purpose of flow regime identification (Hu *et al.*, 2011), and with a Y-shaped pipeline with a pressure drop as the main focus (Guangbin *et al.*, 2010). The best method for solving the complexities of gas-solid flow is by using a visualisation technique that can show the internal phenomena in real time. A traditional technique involves applying particle image velocimetry (PIV) to detect the movements of particles (Miyazaki *et al.*, 1999; Shokri *et al.*, 2017). Another important technique is the visualisation of the internal process by tomography.

1.2 Research Background

Coal power plants currently supply around 41% of the global volume of electricity generation. Table 1.1 shows the five main sources of power generation for Malaysia in 2017 (TNB, 2017). Natural gas remains the most attractive and environmentally friendly resource, since it emits relatively low amounts of CO_2. Burning coal produces almost 14 billion tons of carbon dioxide into the atmosphere each year, most of which emanates from power generation. The problem with natural gas is that it is harder and costlier to store and transport, while oil has a higher price volatility. On the other hand, coal offers a great value and has a stable price on the market. Coal was therefore predominantly used as a fuel between the late 18th and the mid-20th centuries.

Table 1.1: Source of power generation for Malaysia in 2017 (TNB, 2017)

Fuel	Amount (MW)	Percentage (%)
Natural gas	6,956.13	47.94
Coal	4,422.47	30.48
Hydropower	2,654.69	18.29
Oil	213.44	1.47
Renewables	264.12	1.82

The average gross efficiency of a coal power plant is less than 40%, which means that more than 60% is wasted as heat. Coal power plants can therefore be considered primary electricity generators that contribute to global warming due to their high rates of residual heat production (Barker *et al.*, 2007; Lee *et al.*, 2013). As a solution, excess heat is recovered for use in the plant itself or for supply to other processes that need thermal energy. Rodríguez *et al.* (2017) designed a city water heating system with the aim of benefiting both the environment and the citizens using waste heat. Another important aspect is that instead of working on reducing the possible negative environmental impacts, the focus is instead on improvements to the efficiency of electricity generation, such as the use of clean coal technology (Chen & Xu, 2010; Zhang *et al.*, 2016; Zhao & Chen, 2015), the CO_2 Brayton cycle (Mecheri & Le Moullec, 2016) and combined cycle gas turbines (Aminov *et al.*, 2016). The Isogo coal power plant in Japan has introduced smokeless chimney technology, which is relatively economical, environmentally friendly and technologically proven; this has also allowed further improvements in terms of building or expanding existing coal power plants. The analysis of various types of coal has been widely applied due to the importance of coal in the generation of power, and plays an important role in the performance, design, sizing, corrosion, deposition, combustion stability and lifespan of the boiler. Santhosh Raaj *et al.* (2016) used conventional and advanced analytical techniques to characterise coal blends, and a simulation process was also used to characterise the flow mechanism of the coal combustion process inside the boiler (Da Silva, Indrusiak, & Beskow, 2010; Ibrahimoglu, Yilmazoglu, & Cucen, 2016; Schuhbauer *et al.*, 2014).

Tomography is widely utilised in industries such as chemical processing, pharmaceuticals, petroleum, oil, mixing process, metal, environmental, power plants and so forth. Tomography techniques are becoming increasingly important due to their capacity to provide detailed information on the complex internal flow and multiphase behaviour of process units (Holden *et al.*, 1999). Tomography processes, and especially electrical modalities, offer a unique method of solving the complexities of the internal flow without invading that flow (Dyakowski, Jeanmeure & Jaworski, 2000). This approach has been used since the end of the 1980s, based on an online analysis of the internal processes in the factory, to improve the design and operation of equipment, and is a technique for obtaining cross-sectional images of industrial processes. Of the various modalities of electrical tomography, electrical capacitance tomography has a relatively low cost, is a fast imaging process with no radiation, and is non-intrusive and non-invasive.

1.3 Problem Statement

The root cause of high CO_2 production by coal power plants is the low efficiency of burning coal inside the boiler. Research and development are therefore particularly focused on the boiler, as it is the main piece of equipment in a coal-fired power plant. However, less attention has been given to the piping system that supplies coal to the boiler. The main issues related to piping systems are the sedimentation of coal inside the pipe and the non-uniformity of the velocity of coal as it is transferred from the pipe to the boiler. These problems lead to the inefficient transfer of pulverised coal to the boiler system, which generates corrosion inside the pipe, increases the production costs, damages the boiler and reduces energy production while increasing CO_2 emissions. One method that is currently used to measure the sedimentation of coal is based on the measurement of the coal concentration using a thermal probe (Liu *et al.*, 2015) and electrostatic sensor arrays (Qian *et al.*, 2014). The velocity of the pulverised coal is measured using a laser Doppler anemometer (LDA) (Pickett, Jackson & Tree, 1999). This method calculates the particle velocity by receiving scattered light from particles irradiated with two coherent laser beams (Durst *et al.*, 1977). The primary disadvantage of this method is that the velocity of a single particle is measured rather than the velocity of the fluid or bulk solids, and errors may arise if the particles are not uniformly distributed in the flow (Johnson, 1984).

The best technique for characterising multiphase flow phenomena involves visualisation inside the system without invading the flow. Tomography, and especially electrical capacitance tomography (ECT), offers a relatively versatile option for examining online flow phenomena in a non-invasive and non-intrusive way, and techniques have been fully developed for medical purposes and industrial applications. Tomography techniques have significant capabilities in terms of investigating the phenomena inside the piping systems of coal power plants and measuring the velocity of the coal. Cong *et al.* (2013) used ECT to study the flow patterns of coal in a piping system with a linear back projection (LBP) algorithm, while Azzopardi *et al.* (2008) calculated the velocity of pulverised coal using a cross-correlated capacitance value from dual-plane ECT in the time domain. The LBP algorithm is the most well-known technique used with ECT systems as it has high calculation speeds, although its accuracy is low. Cross-correlation in the time domain is normally a time-consuming method of obtaining the velocity.

This research is a pilot study that aims to characterise the gas-solid two-phase flow phenomena inside a piping system. It focuses on the online visualisation of this flow via simulation and experiment. The simulation is

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